The CFEL - ASG End Station for High Resolution X-ray Imaging at LCLS (and other photon sources)
1. MPI-HLL (MPE and MPP)  
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2. PNSensor and PNDetector  
Heike Soltau, Robert Hartmann, Peter Hille, Roman Schindler, Klaus Hoinkis
OUTLINE

Fully depleted, high speed, monolithic, large format pnCCDs are used for spectroscopic and intensity imaging from 50 eV to 35 keV

SDDs
pnCCDs
LSDDs
AvaCCDs
DEPFET APS
gatable DEPFETs
RNDR, BIB
Conclusion, Summary
## Requirements of the FLASH, LCLS and XFEL Photon Counting and Integrating Area Detectors

<table>
<thead>
<tr>
<th></th>
<th>FLASH, LCLS + XFEL</th>
<th>pnCCD system</th>
</tr>
</thead>
<tbody>
<tr>
<td>single photon resolution</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>energy range</td>
<td>$0.05 &lt; E &lt; 24 \text{ (keV)}$</td>
<td>$0.05 &lt; E &lt; 25 \text{ [keV]}$</td>
</tr>
<tr>
<td>pixel size (µm)</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>sig. rate/pixel/bunch</td>
<td>$10^3$ ($10^5$)</td>
<td>$10^3$ - $10^4$</td>
</tr>
<tr>
<td>quantum efficiency</td>
<td>$&gt; 0.8$</td>
<td>$&gt; 0.8$ from 0.6 to 12 keV</td>
</tr>
<tr>
<td>number of pixels</td>
<td>512 x 512 (min.)</td>
<td>1024 x 1024 and 2048 x 2048</td>
</tr>
<tr>
<td>frame rate/repetition rate</td>
<td>10 Hz - 120 Hz</td>
<td>up to 250 Hz</td>
</tr>
<tr>
<td>Readout noise</td>
<td>$&lt; 150 \text{ e}^{-} \text{ (rms)}$</td>
<td>$&lt; 5 \text{ e}^{-} \text{ (rms)}$ (2 \text{ e}^{-} \text{ possible})</td>
</tr>
<tr>
<td>cooling</td>
<td>possible</td>
<td>around - 40º C</td>
</tr>
<tr>
<td>vacuum compatibility</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>preprocessing</td>
<td>no (yes) ?</td>
<td>possible upon request</td>
</tr>
</tbody>
</table>

### Other Information:
- Temperature compatibility:
  - FLASH, LCLS + XFEL: around - 40º C
  - pnCCD system: room temperature possible
- Readout noise is possible upon request.
CCD basics

- full depletion (50 µm to 500 µm)
- back side illumination
- radiation hardness
- high readout speed
- pixel sizes from 36 µm to 650 µm
- charge handling: more than $10^6$ e/ pixel
- high quantum efficiency
How many charges can be stored in one pixel?

What determines the charge handling capacity in a pixel?

Pixel volume:
20x40x12 $\mu m^3 \approx 1 \times 10^4 \mu m^3$

Doping: $10^2$ P per $\mu m^3$

$CHC = 1 \times 10^6$ per pixel

can be increased by external voltages

can be increased by doping
What is limiting the quantum efficiency?

The thickness of Silicon!!

Q.E. = 99 % @ 8 keV
d = 0.5 mm

Q.E. = 22 % @ 24 keV
d = 0.5 mm
Monolithic Integration of optical blocking filters

Silicon entrance window with $x$ nm of SiO$_2$ and $y$ nm of Si$_3$N$_4$ plus $z$ nm of Al (optical shield)

optical light attenuation: $5 \cdot 10^6$

Thin entrance window
Tracks of minimum ionizing particles (mostly muons)
on ground: typ. 1 hit per 10 cm² per sec
can be discriminated by energy cut
\[ \Delta E = 80 \text{ ehp per } \mu\text{m track} \times 3.7 \text{ eV} \]
= 130 keV for a 450 \( \mu \text{m} \) track
Charge collection in the 75 µm large pixels

Beam:
- diameter 10 µm
- hitting pixel center
- incidence angle 45°

10^4 photons at 1 keV
2×10^3 photons at 10 keV
Confronting the Model with Reality: the MESH Experiment - Results

- CCF depends on many parameters: photon energy, detector thickness, potential, temperature, … (drift time)
- Typical values (Gaussian approximation): $\sigma \sim 7 – 9 \, \mu m$ @ 1 keV and low intensity
- Measurements were done with the Al_K line @ 1.5 keV (410 ehp) with 2.5 electrons noise (rms)

![Charge collection function diagram](image-url)
Detector "System" Modeling

Includes:

- gain correction
- offset correction
- mip rejection
- flat field correction
- PSF correction

- \( f(\text{Energy}) \)
- \( f(\text{Intensity}) \)
- \( f(\text{incident angle } \phi) \)
- charge centroid algorithm

Scientific data analysis is ongoing, a GEANT4 based system simulator is being developed.

We need your expected input photon distribution to calculate the response of the full system!
Detectors for FLASH+LCLS+XFEL+Petra III

The full sensitive area of the system is 59 cm² with 75 µm pixels, 1024 x 1024.

Device fabrication is finished now.

Chip 1: area 29.5 cm²
format: 1024 x 512

Chip 2: area 29.5 cm²
format: 1024 x 512

Transfer of signal charges
insensitive gaps: ≈ 800 µm

Hole diameter: 3 mm

Full Frame imaging area per chip: 512 x 1024

Pixel size: 75x75 µm²

Total area per chip: 29.5 cm²

Readout time per frame: 4 ms
i.e. 250 fps
Can be triggered externally

Total sensitive system area: 59 cm

16 ADC outputs

16 ADC outputs
pnCCD: 1024 x 512, 30 cm$^2$

- 1024 pixel, 7.8 cm
- 512 pixel, 3.7 cm
- Area: 29.6 cm$^2$

Imaging
- 7.8 x 3.7 cm$^2$ = 29.6 cm$^2$
- 75 x 75 µm$^2$
- 1024 parallel read nodes
- 2 e$^-$ @ 250 fps

For 1 keV X-rays the system delivers 2k x 2k resolution points.
pnCCDs overlapping in the center

800 µm insensitive gap
Center hole geometry

Hole $r = 1.2 \text{ mm} - 1.4 \text{ mm}$

Insensitive Region $r = 2.2 \text{ mm}$

Guardring structure
The CFEL-ASG Chamber

Reaction microscope: Many particle ion and electron imaging spectrometer
Velocity map imaging
Additional features: Integration of jet-targets, ports for lasers, special injectors, support structures for fixed targets, etc...
The CFEL-ASG Chamber

Detector 1 (D1)
Detector 2 (D2)
MCP particle detector
FEL
2\textsuperscript{nd} particle detector

Imaging system: For a better view the housing of C1 and C2 is drawn transparently. Detector 1 can have any position between $P_{\text{min}}$ with $d(P_{IA};P_{\text{min}}) = 5$ cm and $P_{\text{max}}$ with $d(P_{IA};P_{\text{max}}) = 300$ mm. Detector 2 is mounted fixed at $d(P_{IA};P_{D2}) = 500$ mm.
The Imager of the CFEL-ASG Chamber

details of detector I, 1k x1k pnCCD

Imaging system:  
(a) format 1024x1024, pixel size 75x75 µm², 8x8 cm² focal surface  
(b) center hole, typically 3 mm  
Due to overlap of the two detectors, effective insensitive area can be reduced to 1.6 mm, insensitive gaps: 0.8 mm  
(c) movement in y-direction: up to 45 mm
The Imagers of the CFEL-ASG Chamber

view on detector I+II, two systems 1k x 1k each. Detector 1 is movable, Detector 2 is fix

System alignment:
Detector 1 is movable in Y, Z and X (limited), 400 mm Ø
Detector 2 is fixed, 250 mm Ø
Detectors for FLASH+XFEL+PETRA III

The full sensitive area of the system is 239 cm² with 75 µm pixels, 2048 x 2048

Full Frame imaging, format per chip 1024 x 1024

pixel size 75x75 µm²

total area per chip: 59 cm², per system: 236 cm²

readout time per frame: ≈ 8 ms i.e. ≈ 125 fps

This system is 3 - side buttable, can be extended to a 2048 x 2048 array

devices are scheduled for fabrication end 2010 ready: end 2011

Chip 1: area 59 cm² format: 1024 x 1024

transfer of charges

16 ADC outputs

Lothar Strüder, MPI Halbleiterlabor and Universität Siegen
FLASH, LCLS, SCSS and XFEL systems in 2012

2048 x 2048 CCD array
(resolution points: at least 4kx4k @ 1 keV)

pixel size: 75 x 75 µm²

total area: 236 cm²

readout time: < 8 ms

read noise < 15 electrons

Charge handling capacity: > 1000 photons pp

Energy 0.1<E<24 keV

thickness: 500 µm

operation temperature: -40°C
Present and Future Work

- Operating modes:
  - continuous
  - pulsed sources (fs)
  - pulsed with pulse substructure

- Our developments:
  - FLASH (2007, 2008, 2009, ...) 512 x 256, 3 systems, pnCCD
  - LCLS (2009, 2010, ...) 1024 x 1024, 2 systems pnCCD
  - SCSS (2010, 2011, ...) 1024 x 1024, 1 or 2 systems pnCCD
  - XFEL (2013 - ...) 1024 x 1024 and 2048 x 2048 pnCCD
  - XFEL (2014 - ...) 1024 x 1024, 5 MHz DePFET-APS
Next steps towards the LCLS system

- End of chamber design: end of Oct-08
- First technical drawings available: end of Oct-08
- Ordering of first components: now
- End of fabrication of components: end of Feb-09
- End of chamber assembly: end of Apr-09
- End of pnCCD integration: end of May-09
- End of laboratory tests: end of Jul-09
- End of calibration phase: end of Sep-09
- Transfer to LCLS: beg. of Oct-09
- Start of measurements at LCLS: October 2009
## Properties of the LCLS system in October 2009

- **Position resolution**: 40 µm
- **Resolution elements**: 2000 x 2000 (at least)
- **Format**: 1024 x 1024
- **Physical size (sensitive area)**: 76.8 x 76.8 mm²
- **Frame rate**: 120 Hz
- **Triggerable, threshold**: yes, 25 eV
- **Dynamic range**: 1 to 10,000
- **Electronic noise (rms), E(FWHM)**: > 4 electrons (ΔE ≈ 30 eV)
- **# electron-hole pairs @ 1 keV**: 280
- **S/N ratio @ 1 keV (single photon)**: 56 : 1
- **Radiation hardness**: > $10^{17}$ per pixel

*Data analysis tool plus an instrument simulator*
Conclusions

Phase I
- fast pnCCD systems will cover the parameter space for FLASH, LCLS, SCSS and XFEL (except for the 5 MHz operation)
  format: 1k x 1k, operational in 2009

Phase II
- fast pnCCD systems with a format of 2k x 2k will be operational in 2011/12

Both systems are: highly efficient, high speed, low noise and radiation hard and . . . . . . cosmetically perfect
Recent pnCCDs fabrications

- **Prototype eROSITA version**
  - Format: 256 x 256 x 2 pixel
  - Area: 3.7 cm² + 2.5 cm²
  - Pixel size: 75 x 75 µm²

- **Flight type eROSITA version**
  - Format: 384 x 384 x 2 pixel
  - Area: 8.4 cm² + 5.6 cm²
  - Pixel size: 75 x 75 µm²
Measurements with 512x256 pnCCDs @ FLASH + BESSY

256 parallel low noise readout channels with 2 or 4 output nodes

Frame store area 256 x 256 pixel

Imaging area 256 x 256 pixel
Clusters “in the Flight”

Xe clusters

FEL beam

nozzle

skimmer

cluster beam

CCD camera

beam dump

plane mirror

aperture

VUV scattered light

MCP detector + phosphor screenskimmer

550 nm visible light

aperture

CFEL Detectors

Lothar Strüder, MPI Halbleiterlabor and Universität Siegen
Set-up in T.M. Beamline @ FLASH

- pnCCD1: 10° – 25°
- pnCCD2: 20° – 40°
- pnCCD3: 42° – 80°
Free Electron Lasers

typ. 5,000 X-rays per shot per detector, i.e. $\approx 0.1$ photon per pix.

$E = 90$ eV
$\Rightarrow 25 \pm 1.7$ e-h pairs
ENC = $2.5$ e$^{-}$ (rms)

FWHM: 38.9 eV
Conclusions

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Both systems are: highly efficient, high speed, low noise and radiation hard and . . . . . . cosmetically perfect
The MPI Semiconductor laboratory* at the SIEMENS Research Campus in Munich
(Not) The End